Cloudproxy Nuts and Bolts

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Overview

Cloudproxy is a software system that provides *authenticated* isolation, confidentiality and integrity of program code and data for programs even when these programs run on remote computers operated by powerful, and potentially malicious system administrators. Cloudproxy defends against observation or modification of program keys, program code and program data by persons (including system administrators), other programs or networking infrastructure. In the case of the cloud computing model, we would describe this as protection from co-tenants and data center insiders. To achieve this, Cloudproxy uses two components: a "Host System" (raw hardware, Virtual Machine Manager, Operating System) which provides capabilities described below to the protected program or "Hosted System" (VM, Application, Container).

A key concept for Cloudproxy is program measurement. A Host System measures a Hosted System incorporating the actual binary code of the Hosted System and configuration information affecting its execution resulting in a unique, globally descriptive, unforgeable, identity called the "Hosted System Measurement." Since a Host System knows the "measurement" of each Hosted System it runs, it can store secrets that only that Hosted System will receive[2]. The Host System can also "attest" to statements made by Hosted Systems by incorporating the Hosted System Measurement in statements it signs on behalf of the Hosted System. The upshot of this is that a Cloudproxy Hosted System can be isolated, can use secrets only it knows to encrypt and integrity protect all data it receives, sends or stores, as well as secrets that allow it to securely authenticate itself over an otherwise unprotected network connection. Each Host System can itself be the Hosted System of a parent Host System and each such "child Host System" relies on its parent Host System to protect the keys the child Host System uses to provide services for its Hosted Systems. The "root" or "base" Host System is hardware which, fortunately, is widely available.

Learning how to develop Cloudproxy applications is easily achieved by seeing and understanding fairly simple working code. We developed a simple application, called simpleexample, that is used throughout this paper. Reading this paper in conjunction with understanding simpleexample should enable you to develop Cloudproxy applications within a day or so. The source code for simpleexample is in the Cloudproxy distribution.

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[2] To do this, the Host System must be isolated and have access to secrets only it knows. Given that, the Host System, using its secrets, simply encrypts and integrity protects the Hosted System secrets along with the Hosted System Measurement. It only decrypts those secrets for a Hosted System with the same Hosted System Measurement.

Readers can consult [1] for a fuller description. Source code for Cloudproxy as well as all the samples and documentation referenced here is in [2].

Principal Names in Cloudproxy

Principal names in Cloudproxy (called "Tao Principal Names") are globally unique, general and can represent key based principals, machine based principals, and, most importantly, program based principals. A Tao Principal Name is hierarchical and, in the case of program principals, contains the Hosted System Measurement of as well as the measurements of all its Host and all the Host System's ancestors. For example, a principal rooted in a public key will have the public key (or a cryptographic hash of it) in its name; thus the name is globally unique and unforgeable. Since a program principal has the Hosted System Measurement in its Tao Principal Name as well as the measurement of the Host System and all its ancestors, it too is globally unique and unforgeable

The name for a Hosted System (i.e., a program) running on a "base" Host System identified by a base public key (typically a hardware key) might look something like

```
key([0801100118012245080112410 46cdc82f70552eb...]).Program([25fac
93bd4cc868352c78f4d34df6d2747a17f85...])
```

Here, `key([0801100118012245080112…])` represents the signing key of the (hardware) Host System and `Program([25fac93bd4cc868352c78f4d34df6d2747a17f85...])` is a cryptographic hash of the code and configuration information of the booted Hosted System[3]. If the Host System were a Linux host rooted in a TPM boot, its name would include the AIK of its hardware host at the top level of hierarchy and the PCRs of the booted Linux system, the hash of the Authenticated Code Module ("ACM")[4] that initiated the authenticated boot and the hash of the Linux image and it's initramfs[5] at the second level of the name hierarchy. If the Hosted System was a Linux application whose Host System was a Cloudproxy enabled Linux which itself was hosted by a Hypervisor that booted under a TPM mediated boot, its name would include the AIK at the top level of the hierarchy, the PCR values and boot flags of the hypervisor at the second layer of the hierarchy, the measurement (performed by the hypervisor) of the Linux OS (again naming its code hash, boot flags and initramfs) as well as the measurement (made by the Linux host) of the application code and configuration information (like command arguments) at the third level of the name hierarchy.

In the SimpleExample execution output, analyzed below, there are many more examples of Tao Principal Names.

[3] As indicated by the ellipsis ("…") principal names are often longer and may even contain, say, the full modulus of an RSA public key.
[4] The ACM is a piece of software that controls the authenticated boot of a TPM mediated boot, so it must be included as "configuration information."
[5] Initramfs will have security critical code like the service that implements the Tao so it must be measured along with the kernel image to provide an accurate identity for the "running Linux OS."

The Cloudproxy API

The Cloudproxy programming model is simple and uses only a few API calls. Cloudproxy provides a programming interface in Go or C++ and we refer to the collection of Cloudproxy API's as the "Tao Library."

There are two Cloudproxy principal API interfaces of interest for Go programmers. The first is the Tao API to access functions in a Hosted System. The interface definition is in `$CLOUDPROXYDIR/go/tao/tao.go`. The interface functions are:

```
GetTaoName()returns the Tao principal name of the Hosted System.

ExtendTaoName(subprin auth.SubPrin irreversibly extends the Tao
Principal Name by adding an additional node to the the
hierarchical Tao Principal Name.

GetRandomBytes(n int) returns n cryptographically secure random
bytes.

Rand() returns and io.Reader for random bytes from this Tao.

Attest(issuer *auth.Prin, time, expiration *int64, message
auth.Form) returns an Attestation from the Host System.  The
(optional) issuer, time and expiration will be given default
values if nil; the message attested to is a form in the Tao
authorization language.

Seal(data []byte, policy string) returns a blob encrypted and
integrity protected by the Host System containing the data,
policy and measurement of the Hosted System in a form suitable
for Unseal.

Unseal(sealed []byte) decrypts and returns the data and policy
string, if access complies with the policy which usually includes
having the embedded Hosted System measurement match the embedded
measurement.
```

There are a few additional Tao functions, commonly used by Hosted Systems related to domain management and communications supporting local data storage, and the guards employed for authorization decisions.:

```
CreateDomain(cfg DomainConfig, configPath string, password
[]byte) (*Domain, error)

DomainLoad is used to store and retrieve Program Certificates and
sealed policy data.
```

```
Parent()which gets the parent interface to the Tao.  If t :=
tao.Parent(), for example, we'd call Attest as t. Attest(issuer,
time, expiration, message.

DialTLS(network, addr string) creates a new X.509 certs from
fresh keys and dials a given TLS, returns connection.

DialWithKeys(network, addr string, guard tao.Guard, v
*tao.Verifier, keys *tao.Keys) connects to a TLS server using an
existing set of keys, returns net.Conn.

Listen(network, laddr string, config *tls.Config, g tao.Guard, v
*tao.Verifier, del *tao.Attestation) returns a new Tao-based
net.Listener that uses the underlying crypto/tls net.Listener and
a Guard to check whether or not connections are authorized.

ValidatePeerAttestation(a *Attestation, cert *x509.Certificate,
guard Guard) checks a Attestation for a given Listener against an
X.509 certificate from a TLS channel.

(l *anonymousListener) Accept() (net.Conn, error) Accept waits
for a connect, accepts it using the underlying Conn and checks
the attestations and the statement.
```

The Tao Library also contains helper functions to build and verify Program Certificates, perform common crypto tasks like key generation and establish the Tao Channel. These are most easily understood by looking at the simpleexample code below.

Finally, the Tao Library has rather extensive and flexible authorization support. Authorization decision are performed by *guards*.

Current guards include:

- The liberal guard: this guard returns true for every authorization query
- The conservative guard: this guard returns false for every authorization query
- The ACL guard: this guard provides a list of statements that must return true when the guard is queried for these statements.
- The datalog guard (used in the example below): this guard translates statements in the CloudProxy auth language (see `$CLOUDPROXYDIR/go/tao/auth/doc.go` for details) to datalog statements and uses the Go datalog engine from github.com/kevinawalsh/datalog to answer authorization queries. See install.sh for an example policy.

A brief description of the guards and authorization language appears in appendix 1 but you don't need to understand the authorization language to understand simpleexample.

Examples of all these calls (and their arguments), except for Rand, appear in the simpleexample code.

The second API is the Host API used by Host Systems and defined in `$CLOUDPROXYDIR/go/tao/host.go`. It consists of the following calls:

```
GetRandomBytes(childSubprin auth.SubPrin, n int) which returns
random bytes

Attest(childSubprin auth.SubPrin, issuer *auth.Prin, time,
expiration *int64, message auth.Form) which requests the Host
System's Host sign a statement on behalf of

Encrypt(data []byte) returns and encrypted, integrity protected
blob only the Host can decrypt.

Decrypt(encrypted []byte) returns the data protected by Encrypt if
this is the right Host.

AddedHostedProgram(childSubprin auth.SubPrin) notifies host that a
new Hosted System has been created.

RemovedHostedProgram(childSubprin auth.SubPrin) notifies the Host
that a Hosted System has been terminated.

HostName() returns the Principal Name of this Host System.
```

The best way to learn Cloudproxy is by looking at the annotated code in `$CLOUDPROXYDIR/go/apps/simpleexample` using the commentary below.

The Tao Paradigm

The Tao is often used in a stereotypical way which we refer to as the Tao Paradigm. Cloudproxy programs always have policy public keys embedded (PK_{policy}) in their image either explicitly or implicitly[6]. Statements signed by the corresponding private key (pK_{policy}), and only those statements, are accepted as authoritative and acted on by these programs. The policy key(s) plus the Hosted System code and configuration, reflected in its measurement, fully describe how the Hosted System should behave and, hence, an authenticated measurement is a reliable description of expected behavior.

In the Tao Paradigm, when a program first starts on a Hosted System, it makes up a public/private key-pair ($PK_{program}$/ $pK_{program}$) and several symmetric keys that it uses to "seal" information for itself. A Hosted System then "seals," using the Host System interface, all this

[6] Explicitly embedding the key just means that it appears in initialized data measured as part of the program. An example of implicit embedding, which is described in more detail below, is reading in, say, the policy key and extending the identity of the program with that key.

private (key) information[7]. After that, the Hosted System requests an Attestation from its Host System, naming the newly generated $PK_{program}$ and sends the resulting Attestation to a security domain service which confirms the security properties in the Attestation and Host Certificate[8]. If the Attestation and Host Certificate meet security domain requirements, the security domain service signs (with pK_{policy}) an x509 certificate specifying $PK_{program}$ and the Tao Principal Name of the Hosted System. The resulting certificate, called the *Program Certificate*, can be used by any Hosted System to prove its identity to another Hosted System in the same security domain. Program Certificates are used to negotiate encrypted, integrity protected TLS-like channels between Hosted Systems (the "Tao Channel"); Hosted System can share information over these channels with full assurance of the code identity and security properties of its channel peer. Once established, each endpoint of the Tao Channel "speaks for" its respective Hosted System.

Hosted Systems in the same security domain can fully trust other authenticated Hosted Systems in that security domain with data or processing. Typically, a Hosted System uses the symmetric keys it generates and seals at initialization to encrypt and integrity protect information it stores on disks or remotely.

Employing a centralized security domain service eliminates the need for each and every Cloudproxy Hosted System in a security domain to maintain lists of trusted hardware or trusted programs and simplifies distribution, maintenance and upgrade.

Often, Hosted Systems in the same security domain will share intermediate keys to protect data that may be used under many Host System environments. These keys can be shared based on policy-key signed directives as Host or Hosted Systems are upgraded or new systems are introduced in a controlled but flexible way eliminating the danger that data might become inaccessible if a particular Cloudproxy system is replaced or becomes damaged or unavailable. The penultimate section of this paper discusses key management techniques as keys, programs and domain information changes over the lifetime of a Cloudproxy based application.

Hardware roots of Trust

Cloudproxy requires that the lowest level, "booted" system software (the "base system") be measured by a hardware component which provides attest services and seal/unseal services and, usually, some hardware facilities to isolate Hosted Systems. Absent hardware protection, remote users have no principled way to trust the security promises (isolation, confidentiality, integrity, verified code identity) of Cloudproxy since "insiders" might have silently changed security critical software or stolen low level keys.

Cloudproxy supports TPM 1.2 and TPM 2.0 as hardware roots of Trust for Host Systems booted on raw hardware. We have implemented support for other mechanisms and believe adding a

[7] The sample code in `$CLOUDPROXYDIR/go/apps/fileproxy` demonstrates rollback protection for this sealed data and we plan to improve local rollback support in the near future.
[8] The actual attestation being signed by the Host System expressed in a formalized language is $PK_{program}$ speaksfor the Hosted System's Tao Principal Name.

new hardware mechanism is relatively easy. In addition, Cloudproxy also can initialize and run on a “soft Tao” which simulates secure base system protection (but is not secure). This allows for easy debugging.

Once the base Host System is safely measured and booted on a supported hardware, Cloudproxy implements support for recursive Host Systems at almost every layer of software including:

1. A Host System consisting of hardware (e.g. - TPM, SMX) that hosts a VMM which isolates Hosted Systems consisting of Virtual Machines.
2. A Host System running in an operating system which isolates Hosted Systems consisting of processes (or applications).
3. A Host System running in an operating system which isolates Hosted systems hosted consisting of subordinate Operating Systems or Containers.
4. A Host System running in an application (like a browser) which isolates Hosted Systems consisting of sub-applications, like plug-ins.

In all cases, Hosted Systems employ the same Cloudproxy API and can use any non-Cloudproxy native service (for example, any system call in Linux) so the programming model at each Hosted System layer is essentially unchanged from the non-Cloudproxy case.

Sample Applications

This paper is intended to allow you to use Cloudproxy immediately on a Linux based Cloudproxy Host System. To this end we include installation instructions for running under a “soft Tao” and TPM 1.2 based Tao protected hardware with SMX extensions. To facilitate this, we use a standard simple application called, cleverly, simpleexample throughout this paper.

Installing Cloudproxy

First, you should download the Cloudproxy repository from [2]. To do this, assuming you have git repository support, type

git clone https://github.com/jlmucb/cloudproxy,

or,

go get https://github.com/jlmucb/cloudproxy.

This latter command will also install the needed go libraries. You can also download a zipped repository from github. You should probably install this in ~/src/github.com/jlmucb (which we refer to as `$CLOUDPROXYDIR`) to save go compilation problems later. It’s a good idea to put go binaries in `~/bin` as is common in Go. Follow the installation instructions in `$CLOUDPROXYDIR/Doc`; that directory also contains [1] and an up to date version of this document as well as installation instructions for TPM 2.0 capable machines and installation instructions for Cloudproxy enabled KVM hypervisors and Docker containers.

You must also install the Go development tools (and C++ development tools if you use the C++ version) as well as protobuf, gtest and gflags as described in the Go documentation.

Next, compile, and initialize the SimpleExample application in `$CLOUDPROXYDIR/go/apps/SimpleExample` and run it as described in the next section.

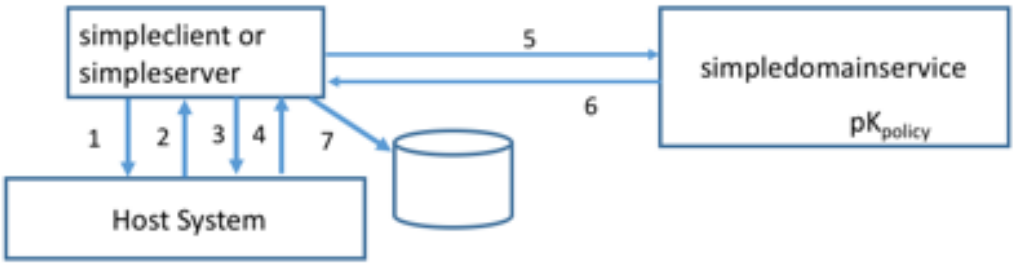
Understanding Simple Example

There are three application components in simpleexample, each producing a separate executable:

1. A Simple Client in `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleClient simpleclient.go`
2. A Simple Server in `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleServer/simpleserver.go`.
3. A Simple Security Domain Signing Service in `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleDomainService/simpledomainservice.go`.

Common code used by the client and server is in `$CLOUDPROXYDIR/go/apps/SimpleExample/taosupport`.

When *simpleclient* and *simpleserver* start for the first time on the Host System, they provide Attestations to *simpledomainservice* and, if the measurements are correct, *simpledomainservice* signs their respective Program Certificates with pK_{policy}. This interaction is depicted below.

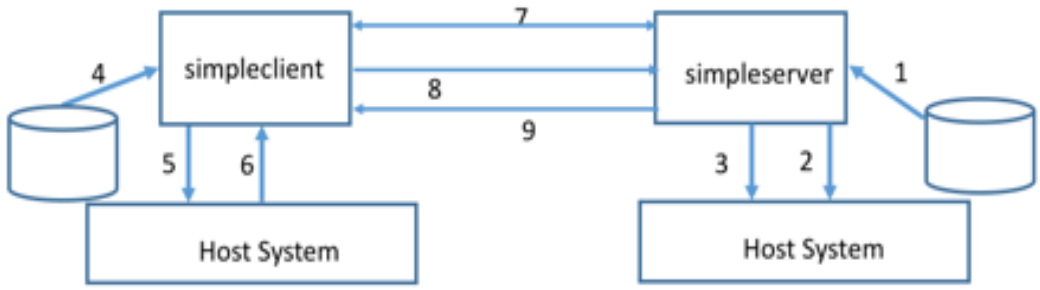


Initialization

1. simpleclient (or simpleserver) generates public/private key pair $PK_{simpleclient}$, $pK_{simpleclient}$. simpleclient requests Host System attest $PK_{simpleclient}$.
2. Host System retuns attestation
3. simpleclient generates additional symmetric keys and request Host System seal symmetric keys and $pK_{simpleclient}$.
4. Host System returns sealed blobs.
5. simpleclient connects to simpledomainservice and transmits attestation.
6. simpledomainservice returns signed Program Certificate.
7. simpleclient stores sealed blobs and Program Certificate for later activations.

Initialization

After initialization of keys and secrets, *simpleserver* waits for *simpleclient* instances to request their secret (which is client dependent). Each *simpleclient* instance uses a Tao Channel to contact the *simpleserver* to learn its secret. We don't implement rollback protection or distributed key management for intermediate secrets in simpleexample just to keep the example as simple as possible. *simpledomainservice* is the domain service for simpleexample.



Operation

1. Simpleserver reads previous sealed blobs and Program Certificate.
2. Simpleserver requests Host System unseal blobs yielding symmetric keys and private program key.
3. Host system returns unsealed blobs.

4. Simpleclient reads previous sealed blobs and Program Certificate.
5. Simpleclient requests Host System unseal blobs yielding symmetric keys and private program key.
6. Host system returns unsealed blobs.

7. Simpleclient and simpleserver open encrypted, integrity protected channel using their program keys and certificates.
8. Simpleclient transmits a request to retrieve secret.
9. Simpleserver retruns secret.

Operation

We describe the Cloudproxy API, compilation and installation, execution and output of the Go version of simpleexample in the sections below. We also general description critical Cloudproxy elements used in the simpleexample to help you get used to the programming model. Since the domain service does not use the Cloudproxy API extensively, we don't describe code in detail here although `$CLOUDPROXYDIR/go/apps/SimpleExample/simpledomainservice` contains a full working version. A corresponding C++ version of simpleclient, simpleserver and simpledomainservice is described in Appendix 2.

Although simpleexample is very simple, the Tao relevant code in simpleexample can be used with little change even in complex Cloudproxy applications.

Simple Client in Go

simpleclient is implemented as a single go file in `$CLOUDPROXYDIR/go/apps/simpleexample/simpleclient/simpleclient.go` together with some common Tao based code in `$CLOUDPROXYDIR/go/apps/simpleexample/taosupport`. You should open that file and read the code as you read this.

simpleclient parses the flags it was called with and calls TaoParadigm with the location of its domain configuration information, the directory in which simpleclient can save its local files (like sealed keys and certs) and a preallocated `TaoProgramData` object, which is populated with all important Cloudproxy keys and data subsequently required by a Cloudproxy application. If successful, TaoParadigm returns a filled taosupport.TaoProgramData object containing the policy cert for the domain and simpleclient's Tao Principal Name, symmetric keys, Program Key and Program Cert.

TaoParadigm is a support function that uses the Tao API and it's described below. Note that simpleclient erases its keys (defer taosupport.ClearTaoProgramData(&clientProgramData)) after completing the request.

simpleclient then calls OpenTaoChannel to open up a Tao Channel with simpleserver. If successful, OpenTaoChannel returns the channel stream as well as the Tao Principal Name of the simpleserver it connected to.

Finally, simpleclient sends a request for its secret and calls GetResponse to retrieve simpleserver's response. If the request was successful, it prints its secret.

Simple Server in Go

simpleserver is implemented as a single go file in go/apps/simpleexample/simpleclient/simpleserver.go together with some common Tao based code in go/apps/simpleexample/taosupport. You should open that file and read the code as you read this.

Just as simpleclient, simpleserver parses the flags it was called with and calls TaoParadigm with the location of its domain configuration information, the directory in which simpleserver can save its local files and a preallocated `TaoProgramData` object. As above, TaoParadigm returns a filled taosupport.TaoProgramData containing the policy cert for the domain and simpleserver's Tao Principal Name, symmetric keys, Program Key and Program Cert.

simpleserver sets up cert chain rooted in the Policy Certificate to validate Program Certificates it received from peer clients, and listens over the indicated socket. In addition to the client Program Certificate, the TLS handshake uses simpleservers Program Certificate. After initialization, simpleserver then loops through a standard socket acceptance loop, waiting for a successful client connections. Each successful connection is serviced in a separate thread. A successful client connection will result in a valid peer Certificates for the corresponding simpleclient obtained and verified by the TLS handshake. Simpleserver retrieves extracts the simpleclient's Tao Principal Name from the simpleclient Program Certificate (which appears in the Organizational Unit of its x509 name) and dispatches a thread [go serviceThead(ms,

clientName, serverProgramData)] with the per-client service channel, client Principal Name and simpleserver `TaoProgramData` object.

serviceThead loops through a standard service request-response loop. It calls taosupport.GetRequest on the designated service channel to get requests. If it receives a valid request, it calls HandleServiceRequest to service the request. There is only one valid request which is "give me my secret," after reciving such a request, HandleServiceRequest makes up a client specific secret consisting of the the clientName with "43" appended and return is using taosupport.SendResponse. After the first successful request, simpleserver terminates.

Some Common code in Go

TaoParadigm loads the domain information from the provided configuration file [simpleDomain, err := tao.LoadDomain(*cfg, nil)] and retrieves the policy certificate from the domain information. It hashes the policy cert and uses this to Extend the Tao Principal Name which binds the policy key to the current program identity.

Next TaoParadigm calls LoadProgramKeys, which retrieves previously created sealed symmetric keys and Program Key along with the Program Certificate (if they exist), from the application directory, otherwise it returns nil. If the sealed sealed symmetric keys were recovered, it unseals them, otherwise (via the call to InitializeSealedSymmetricKeys), it generates new keys, seals them and saves them to the correct file in the application directory. If the sealed Program Key exists, it unseals the Program Key, otherwise, TaoParadigm generates a new program key, builds a certificate signing request, attests the new Program public key and communicates with the domain signing service to have a Program Certificate signed by the policy key. This is done by InitializeSealedProgramKey which we describe further below. Before returning, InitializeSealedProgramKey, seals the private Program Key, and stores the sealed key and certificate in the application area and returns the new Program Key and Program Certificate.

Finally, TaoParadigm fills the TaoProgramData object with the symmetric keys, program key, policy certificate, program certificate and the location of application store; it then returns.

InitializeSealedProgramKey carries out the heart of the Cloudproxy key management service, so it and its callees are worth a little further discussion. InitializeSealedProgramKey calls CreateSigningKey which generates a new Program Key, builds an x509 certificate request which includes the Hosted System's Tao Principal Name, and self-signs that certificate request. It then constructs a statement in the authorization language that says "PrincipalName(Program-Key) speaksfor PrincipalName(Program)" where each "PrincipalName" is the canonical Tao Principal name of, respectively, the new key and the Program's Tao Principal Name. This is called, a delegation statement. CreateSigningKey then requests the Host System (via the Tao Interface) attest to the delegation statement. The attestation includes the delegation, the Measurement of the Hosted System and is signed by the Host System. The resulting attestation means "HostSystem(attestation-key) says PrincipalName(Program-Key) speaksfor

PrincipalName(Program)." This attestation along with any relevant supporting certificates, is transmitted to the domain signing service (simpledomainservice) via the call to RequestDomainServiceCert. The domain service, if the Hosted System measurement conforms to the list of "trusted programs" in the domain, signs the Program Certificate with the (private portion of) the policy key and returns it. The resulting Program Certificate means "Policy-Key says PrincipalName(Program-Key) speaksfor PrincipalName(Program)." Any relying program in the domain receiving the Program Certificate from a communicating program can verify the Program Certificate (using the public portion of the policy) and demand the communicating program "prove possession" of the private portion of the Program Key. Such a proof cryptographically authenticates the communicating program and the Tao properties under which it was created.

Two programs in the security domain, one acting as a client and one acting as a server, use their Program Keys to open an encrypted, mutually authenticated, integrity protected TLS channel. Once this channel is established each program know "the channel speaks for the peer Program Principal." The client side of this channel negotiation is accomplished by the program OpenTaoChannel. It simply uses the Program Key of the client (and the received Program Certificate of the server which is authenticated by the policy key) to open the TLS channel. OpenTaoChannel returns the resulting bidirectional channel handle and the Tao Principal Name of the server. The corresponding code in the server to open the channel is in simpleserver and uses its Program Key and Program Certificate.

GetRequest, SendRequest, GetResponse, SendResponse are simple helper functions to get and send requests and responses. Protect and Unprotect are simple functions to encrypt and decrypt files protected by a Hosted System's symmetric keys.

A Hosted System can also ask the Host System to measure and start other programs. We used a utility (tao run, see below) to start simpleclient, simpleserver and simpledomainservice during initialization (and described below) so there was no need to do this in the sampleexample code. Starting a Hosted System varies a little depending on the Host System environment. To see how this is done in programmatically Linux, consult `$CLOUDPROXYDIR/go/apps/tao_launch`.

We should mention that simpleexample was meant mainly to be instructive (but correct!) so we sometimes repeated code that could have been accessed in the Tao Library. We also opted for simple, transparent constructions in Go sometimes at the expense of being "idiomatically correct." The `TaoProgramData`, for example, duplicates some data structures in the Tao Library and is defined to simplify and clarify the actual Tao Data but it can be replaced.

We don't describe simpledomainservice here since it does not directly call the Tao interface. You can find other example applications in `$CLOUDPROXYDIR/go/apps/demo` and a more complex example in `$CLOUDPROXYDIR/go/apps/fileproxy`.

Finally, Appendix 1 has a brief description of the Datalog policy engine and rules.

Configuring, compiling and running SimpleExample

When the Tao Host System starts, it requires several kinds of information:

- A public key that roots the *Tao* on the hardware,
- Host data, including the mechanism used to communicate between the Hosted System and the Host System, rules affecting which Hosted Systems the Host System should run, and, in the case of a hardware rooted Host System, the hardware mechanism that is employed (e.g., TPM 1.2 or TPM 2.0).
- Domain data (in our case for the simpleexample domain) including the policy key and corresponding private key, and the self signed policy cert.

In addition, we need an implementation for the "Host System" which incudes support for the host including support the host's isolation mechanism (processes in Linux) and communications channels used to communicate with Hosted Systems. In our case, the Host System is Linux and the implementation (whether using a soft tao, TPM 1.2 or TPM 2.0) is *linux_host*[9].

The public key rooting the hardware tao is usually produced by a TPM utility; in the TPM 1.2 nomenclature, this is called the AIK. The public key rooting the TPM 2.0 is the endorsement key. In our demo, we use a "soft tao" which is rooted in a key.

The Host Data consists of the Host Certificate (used to validate nested Host System Attestation) and it's sealed keys and data, stored in `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleDomain/domain.simpleexample/linux_tao_host`.

The Domain data includes the policy key and corresponding (encrypted) private key, hostname, host type and communications channel used between the Host System and its Hosted Systems, information related to the guards used[10] as well as signatures over the binaries that are part of the domain (if the Host System limits what Hosted Systems it will run, in our case, these are the *simpleclient* and *simpleserver* binaries).

In simpleexample, all domain information is contained in files in `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleDomain/domain.simpleexample`.

Other sub-directories of `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleDomain/domain.simpleexample`, namely, `SimpleClient`, `SimpleServer` and `SimpleDomainService` contains data files stored and retrieved by these programs like sealed keys and Program Certificates.

[9] linux_host is also the implementation used by a KVM Host System and Docker containers and in fact, all Host Systems running on Linux.
[10] Look at `$CLOUDPROXYDIR/go/tao/domain.go` for further details.

There is a single utility, called *tao,* which initializes this domain data, activates the tao host and runs the applications. We provide shell scripts to call *tao* with the right arguments, these scripts are in SimpleDomain.

The scripts use several path variables, namely:

```
TAO_HOST_DOMAIN_DIR=~/src/github.com/jlmucb/cloudproxy/go/apps/simpleexam
ple/SimpleDomain
OLD_TEMPLATE=$TAO_HOST_DOMAIN_DIR/domain_template.simpleexample
DOMAIN=/Domains/domain.simpleexample
TEMPLATE=/Domains/domain_template.simpleexample
BINPATH=~/bin
```

In addition, we need a generic domain template. We have provided a sample template in *SimpleDomain/domain_template.simpleexample*. However, you can generate such a template by running *gentemplate*. "*gentemplate*" consists of:

```
$BINPATH/tao domain init -tao_domain $DOMAIN -config_template $TEMPLATE -
pass "xxx"
/home/jlm/src/github.com/jlmucb/cloudproxy/go/run/scripts/domain_template
.pb > $TEMPLATE \
sed "s/REPLACE_WITH_DOMAIN_GUARD_TYPE/Datalog/g"
```

This template contains information included in the policy cert, the basic datalog rules used by the domain when authenticating images and the location of the images which must be measured and recorded in the policy rules.

To initialize simpleexample, first, we must initialize the directory that will hold domain information. Because of a limitation in one of the Go libraries, Domain paths cannot be too large. We keep all out domains in `/Domains` and we keep the simpleexample domain information in `Domains/domain.simpleexample`, although you can put them elsewhere as long as the path name is short enough.

To do this, we do

```
mkdir /Domains
```

(if that directory does not already exist) and then call *initidomainstorage*. "*initidomainstorage*" sets up the storage hierarchy; it consists of:

```
#
source ./defines
if [ -e $DOMAIN ]
then
  ls -l $DOMAIN
else
  mkdir $DOMAIN
fi
cp $OLD_TEMPLATE $TEMPLATE
source ./defines
if [[ -e $DOMAIN/SimpleClient]]
then
  echo "$DOMAIN/SimpleClient exists"
else
  mkdir $DOMAIN/SimpleClient
```

```
  echo "$DOMAIN/SimpleClient created"
fi
if [[ -e $DOMAIN/SimpleServer]]
then
  echo "$DOMAIN/SimpleServer exists"
else
  mkdir $DOMAIN/SimpleServer
  echo "$DOMAIN/SimpleServer created"
fi
if [[ -e $DOMAIN/SimpleDomainService]]
then
  echo "$DOMAIN/SimpleDomainService exists"
else
  mkdir $DOMAIN/SimpleDomainService
  echo "$DOMAIN/SimpleDomainService created"
fi
```

To initialize the (soft) key, call *initkey*, which does the following:

```
#
source ./defines
if [[ -e $DOMAIN/linux_tao_host ]]
then
  echo "$DOMAIN/linux_tao_host exists"
else
  mkdir $DOMAIN/linux_tao_host
  echo "$DOMAIN/linux_tao_host created"
fi
KEY_NAME="$($BINPATH/tao domain newsoft -soft_pass xxx -config_template
$TEMPLATE $DOMAIN/linux_tao_host)"
     echo "host_name: \"$KEY_NAME\"" >> $TEMPLATE
```

"`newsoft`" means generate a new soft key. The arguments following the flags "`-config_template -tao_ -pass`" specify respectively the location of the template, the location where the domain information is stored and the password protecting the private policy key. This produces the xxx file containing root Tao key. To use a TPM based Host System, you'd call a corresponding program to put the AIK in template.

The following commands are collected in the *runall* script. So from this point on, you can just type *runall* to run simpleexample. From now on, you should run the programs as root.

First, we compile the programs comprising simpleexample, namely *simpledomainservice*, *simpleserver*, and *simpleclient*. Copy the images to `/Domains` because *initdomain* expects the images to be there when it measures the program images. Next, we need to initialize the domain information.

To initialize the domain, call *initdomain* which consists of the following:

```
#
source ./defines
$BINPATH/tao domain init -tao_domain $DOMAIN -config_template $TEMPLATE -
pub_domain_address "127.0.0.1" -pass xxx
$BINPATH/tao domain policy -add_host -add_programs -add_linux_host -
add_guard -tao_domain \
      $DOMAIN -pass xxx -config_template $TEMPLATE
```

The first call produces the files in `$DOMAIN/linux_tao_host/{cert,keys,host.config}`. The second measures the applications in the domain; these programs should have previously been copied into /Domains.

To initialize the (Linux) host, call *inithost* which does the following:

```
$BINPATH/tao host init -tao_domain $DOMAIN -hosting process -root -pass
xxx
```

This generates linux host configuration information stored in the `$DOMAIN/SimpleDomain/domain.simpleexample/linux_tao_host directory`. The argument to the "`-hosting`" flag is the kind of child hosts, namely, Linux processes. The "`-root`" flag means this is a "root" host (i.e. – the lowest level Tao). For hosts stacked on other hosts, we would use the "`-stacked`" flag. For example,

```
$BINPATH/tao host init -tao_domain $DOMAIN -hosting process -stacked -
parent_type tpm
```

To run our development Host System[11], call *runhost*, which consists of:

```
$BINPATH/tao host start -tao_domain $DOMAIN -host linux_tao_host/ -pass
xxx &
```

The argument to the "`-host`" flag is the subdirectory of SimpleDomain/domain.simpleexample that contains the host information.

Finally, to run a Hosted System, like *simpleclient*, we would say:

```
$BINPATH/tao run $BINPATH/simpleclient -tao_domain $DOMAIN &
```

Some further observations: The password supplied in the calls to `tao domain init` and `tao domain policy` protect access to the policy private key. The password supplied to the `tao newsoft`, `tao host init` and `tao host run` protect the soft host private key; this password is usually not the same as the key protecting the policy private key. `linux_host`, which implements the Linux Host, uses the rules generated by `tao domain policy` to decide whether to run an application.

Often, a Host System does not use application security domain rules to determine what to run and, in fact, will run any Hosted System. This can be accomplished with the inclusion of the rule:

```
LinuxHost(x)
(forall P: forall T: forall H: TrustedHost(T) and LinuxHost(H) and
```

[11] In a production system, the Host System would have already been started in the host's initialization scripts.

```
Subprin(P, T, H) implies TrustedLinuxHost(P))
(forall P: Program(P))
(forall P: forall Q: forall H: Program(Q) and TrustedLinuxHost(H) and
Subprin(P, H, Q) implies MemberProgram(P))
```

where x is the measurement of the *linux_host* or an "AllowAll" policy. As you become familiar with the Datalog rules, you can apply them flexibly but that is a distraction in SimpleExample.

To summarize, to run the tests:

```
cd ~/src/github.com/jlmucb/cloudproxy/go/apps/simpleexample/SimpleDomain
./gentemplate
./initdomainstorage
./initkey
sudo bash
./runall
```

After running the programs, copy the *clean* script from `~/src/github.com/jlmucb/cloudproxy/go/apps/simpleexample/SimpleDomain` into `/Domains/domain_simpleexample`, cd to the `/Domains/domain_simpleexample` and run clean from there. Make sure you kill previous instances of *linux_host*, *simpledomainservice*, *simpleserver* and *simpleclient* before re-running *runall*; you need not rerun *gentemplate*, *initdomainstorage* or *initkey*.

What the output from SimpleExample teaches us about the Tao

The most concrete way to understand Cloudproxy is to follow the code example and the output. Here is a brief description of the output of the Go version of SimpleExample using a "soft" tao.

In our execution setup, recall that the domain information is in `/Domains/domain.simpleexample`; this includes the template, tao prepared configuration files and three directories: `SimpleClient, SimpleServer` and `SimpleDomainService` which are directories in which application information (mostly sealed keys) are stored for, respectively, `SimpleClient, SimpleServer` and `SimpleDomainService`. Binaries are stored in the directory `~/bin` as is customary in go.

In the repository, there are also three shell scripts to facilitate running the examples. The script compile compiles the applications and puts them into bin. After making the directory, `/Domains`, use *initdomainstorage* to initialize the storage areas. Copy the script clean into `/Domains/domain.simpleexample/SimpleDomain` and make it executable.

Thereafter, modify any code you wish to and run *compile* in `$CLOUDPROXYDIR/go/apps/SimpleExample/SimpleDomain` to compile the programs. ***Then as root***, run *runall* to run SimpleExample. After it runs, you can run *clean*, in `/Domains/domain.simpleexample/SimpleDomain`, to erase the output files. *clean* runs a

ps aux | fgrep simple at the end to tell you what lingering processes to kill (kill -9) so you can run subsequent tests.

Our example uses the Datalog authorization subsystem so system rules are expressed in the Datalog policy language. Example statements in Datalog can be seen in the template file.

When you look at the output, you'll notice, at the beginning:

```
Warning: Passwords on the command line are not secure. Use -pass option
only for testing.
Warning: Passwords on the command line are not secure. Use -pass option
only for testing.
Warning: Passwords on the command line are not secure. Use -pass option
only for testing.
Warning: Passwords on the command line are not secure. Use -pass option
only for testing.

Linux Tao Service (key([0801100118012245080112410431 0f3c0d7c5ff1...]))
started and waiting for requests

2016/02/20 11:27:13 simpledomainservice: Loaded domain
2016/02/20 11:27:13 simpledomainservice: accepting connections
```

This indicates that the *linux_host, simpledomainservice, simpleclient* and *simpleserver* have been initialized. The second section shows that the *linux_host* for the soft tao (with the indicated key) has started. The final section indicates that the domain service is started and waiting for request.

Next, you'll notice,

```
TaoParadigm: my name is
key([08011001180...]).Program([94d80d932fbc...]).key(f3169de17b1032dde2
30423f7d11dde89c143de147188fa67acf613d63da0420)
```

This is from *simpleserver*, and it is the Tao Principal Name of your *simpleserver* program, running on your Host System, after it has been extended with the hash of the loaded policy certificate. If you look at the source code for *simpleserver*, you'll notice that the policy key is not embedded in the code; if it had been, the policy key would be reflected in the program measurement. Instead, we read in the policy key cert and extend the *simpleserver* Tao Principal Name with the hash of the self-signed policy cert. The Tao Principal Name is hierarchical. The first segment, "`key([08011001180...])`", describes the host root[12]. The second segment, "`Program([94d80d932fbc...])`", describes the *simpleserver* program reflecting its measurement. The third segment, "`key(f3169de17b1032dde230423f7d11dde89c143de147188fa67acf613d63da0420)`"

[12] If the root host had been a TPM, the name would include the TPM's AIK, and the contents of PCR 17 and 18 which contain the measurement of the booted Linux, extended with the initramfs which contains all the security critical files used by the Linux instance

, describes the policy key as noted above. Observe that the Tao Principal Name fully reflects all the program code as well as the policy it will execute (as represented by the policy key).

For the rest of this description, we will simplify terms like "`Program([94d80d932fbc...])`" as "`Program(program-measurement)`".

Next, notice the statement:

```
simpledomainservice, speaksfor: key(simpleserver_program_key) speaksfor
key(host-key).Program(simpleserver-measurement).key(policy-key)
```

This is the statement that TaoParadigm will use to request an attestation from the Linux Host System. The resulting Host System supplied attestation is

```
key(host-system-key) from notBefore until notAfter says [simpleserver-
program-certificate] speaksfor key(linux-host).Program(simpleserver-
measurement).key(policy-key)
```

This statement is sent to the domain service which, after checking the measurements and domain policy signs a certificate (with pK_{policy}) that includes the statement

```
key(policy-key) from notBefore until notAfter says [simpleserver-
program-certificate] speaksfor key(linux-host).Program(simpleserver-
measurement).key(policy-key)
```

This is the *simpleserver* Program certificate. *Simpleserver*, as we described in the code annotations, stores this certificate, and sealed versions of the corresponding private *simpleserver* ProgramKey and SymmetricKeys. Decrypted and useable versions of these keys are populated in *serverProgramData* by *TaoParadigm*.

After initialization, *simpleserver* waits for client connections.

simpleclient meanwhile, goes through the same *TaoParadigm* initialization (which is not duplicated here) obtaining its Program certificate. *ServerClient* calls *OpenTaoChannel* with it's Program Cerificate and corresponding key. You'll notice, later in the output, that *simpleserver* opens a secure channel with a peer

```
key(linux-host).Program(simple-client-measurement).key(policy-key)
```

That peer is just your *simpleclient*. Normally, the Host System on which *simpleclient* runs will be different from the one *simpleserver* runs although in our case, they run on the same host.

Finally, you'll notice that *simpleserver* receives a request

```
2016/02/20 11:27:16     message type: 1
2016/02/20 11:27:16     request_type: SecretRequest
```

and returns the secret which is received by simpleclient as

```
simpleclient: secret iskey(linux-host).Program(simpleclient-
measurement).key(policy-key)43
```

simpleclient encrypts and integrity protects the secret with its symmetric keys and the process concludes.

We have only discussed the major output elements here. Your output will contain much more including log messages from *simpledomainserver*.

The certificate for the simpleclient (which is in `/Domains/domain.simpleexample/SimpleClient/signerCert)` is:

```
Certificate:
    Data:
        Version: 3 (0x2)
        Serial Number: 1455996433984 (0x15300267640)
    Signature Algorithm: ecdsa-with-SHA256
        Issuer: C=US, O=CloudProxy, OU=, ST=WA, CN=SimpleExampleTest
        Validity
            Not Before: Feb 20 19:27:16 2016 GMT
            Not After : Feb 20 19:27:16 2017 GMT
        Subject: C=US, O=Google,
OU=key([0801100118012245080112410431 0f3c0d7c5ff1490ace20f167e7de1d5c6847c
84d498c3b4a8087031b49d9a38e7e59f4c5e4f23adc6ce2e394c7ac48923bcfcd7446bba0
f86ef8bbdf89b6d5]).Program([d38d94100ae2bb57cccb97cb347ab060fb28c382bafe1
38f253fd19b491b1a15]).key(f3169de17b1032dde230423f7d11dde89c143de147188fa
67acf613d63da0420), ST=, CN=localhost
        Subject Public Key Info:
            Public Key Algorithm: id-ecPublicKey
                Public-Key: (256 bit)
                pub:
                    04:7a:d5:40:f6:80:fd:73:a5:80:b8:88:57:7c:60:
                    6d:87:b6:78:4a:3f:fc:1c:cc:40:af:34:2d:98:31:
                    02:21:02:71:65:66:7f:90:49:91:88:91:21:43:c7:
                    f5:50:de:0a:7c:58:c8:6c:10:06:46:fc:3c:1a:a1:
                    bb:c7:20:c6:83
                ASN1 OID: prime256v1
        X509v3 extensions:
            X509v3 Key Usage: critical
                Key Agreement, Certificate Sign
            X509v3 Extended Key Usage:
                TLS Web Server Authentication, TLS Web Client
Authentication
    Signature Algorithm: ecdsa-with-SHA256
         30:44:02:20:0c:a0:99:55:79:0d:b7:26:20:07:38:03:da:ba:
         ff:28:0c:fd:94:f6:4e:5f:b1:ad:41:11:89:42:61:fd:5b:e7:
         02:20:7f:26:62:ee:2a:4c:90:e4:f4:7c:d6:c6:2c:b6:1d:db:
         d8:4a:bc:b9:60:26:aa:80:e8:bf:74:bd:ee:34:cb:fe
```

You'll notice that `/Domains/domain.simpleexample/SimpleClient/` also contains the files

sealedsigningKey (*simpleclient's* sealed program private key), retrieved_secret (the "secret" encrypted with *simpleclient's* symmetric keys) and sealedsymmetricKey (*simpleclient's* sealed symmetric keys).

Running SimpleExample on real TPM-enabled machines

Complete instructions on installing and deploying Cloudproxy on real TPM enabled machines using KVM, Linux and Dcker are in [5]. You should be able to run simpleexample on any of those systems.

Upgrade and key management scenarios

Since sealed material is only provided to a Hosted System with exactly the same code identity that sealed the material running on the exact same Host System, while isolated by that Host System, you may be worried about lost data when a Hosted System breaks or becomes unavailable or limitations that may affect key management, software upgrade or distribution when the Hosted System runs on other Host Systems. In fact, it is rather easy to accommodate all these circumstances, and many others, efficiently, securely and in most cases automatically using Cloudproxy, *provided* Cloudproxy applications make provisions for this during development.

Below are a few sever example key management techniques that can be used when a Cloudproxy application is upgraded, a new Cloudproxy application (in the same security domain) is launched, or as applications migrate to other Host Systems. All these mechanisms preserve the confidentiality and integrity of all Cloudproxy applications and their data.

There is a discussion of many of the mechanisms, as they might affect client software used across different security domains, by users with no control over the application code while supporting consumer transparency (the most challenging case) in [4]. Here we restrict ourselves to cooperating server applications for simplicity.

To ease description, imagine all application data is stored locally or remotely and probably redundantly in encrypted, integrity protected files. Each file is encrypted and integrity protected with individual file keys and each file key is itself encrypted and integrity protected with a group sealing keys. Different groups of file keys are protected by different sealing keys to reduce the risk of universal compromise. Every key has exposed meta data consisting of a globally unique name for the entity it protects, the key type and an "epoch." Epochs increases monotonically as the keys are rotated[13]. As keys for a new epoch become available, the objects they protect are re-encrypted, over a reasonable period of time (the Rotation Period). During this time, keys for the prior epoch are available and can be used to decrypt objects; however, as soon as new epoch keys are available, all new data is encrypted with the new epoch keys. At the end of the

[13] And you certainly should rotate keys as part of effective cryptographic hygiene!

Rotation Period, once applications have confirmed that all data is protected with the keys from the most recent epoch, old epoch keys are deprecated.

The first option to deal with "brittle keys" protecting application data is standard: use a distributed key server which authenticates a Tao Program and provisions symmetric keys for data over the authenticated, encrypted, integrity protected Tao Channel. In this case, Cloudproxy applications do not locally store data protection keys[14] but contact a key server (over a Tao Channel). The key server (which does key rotation, etc., as many do) authenticates the Hosted System that needs keys and verifies that it is authorized to receive those keys, and if so, they are transmitted over the Tao Channel. Hosted Systems can be upgraded and all authorization policy can be maintained by the key service in this model. Note that application upgrade is automatic when you use this option even when the policy keys change: New versions of Hosted Systems simply re-initialize (get new program keys and certificates) using the (centralized or distributed) security domain service and no special provision, aside from current policy at the security domain service, need be provided[15].

Sample code for such a keyserver is `$CLOUDPROXY/go/support_infrastructure/CPSecretService`. Support libraries that allow you to build symmetric key trees (and partitioned secrets) with key rotation support in the style suggested above are in `$CLOUDPROXY/go/support_libraries/protected_objects, rotation_support`. This mechanism allows you to cache sealed keys using the key tree to avoid contacting a keyserver on each activation but you will likely want to add a "key change" notification as new key epochs are introduced.

An alternative, less centralized, key rotation mechanism, which we call certificate based key disclosure, allows individual Hosted Systems maintaining their own keys to protect files as well as perform key rotation themselves. When software is upgraded or new programs are introduced, the new programs or upgraded programs come with a certificate signed by the policy key that instruct one Hosted System to disclose these keys to the new version (or new) Hosted System. Since this can result in lost data if a Host System becomes unavailable, Hosted Systems would likely distribute these keys to different instances on different machines to ensure continuity.

Support libraries that implement certificate based key disclosure are in `$CLOUDPROXY/go/support_libraries/secret_disclosure_support`.

Finally, when new data protection keys are established for an application task, Hosted Systems can contact a domain service to receive intermediate keys for registered files or file classes. These keys can be sealed using the Host System provided Seal and used without contacting the service each time the Hosted System starts. This mechanism places additional

[14] Although they may cache such keys --- see below.
[15] Many events may cause such a policy change including a determination that previously trusted hardware elements have been compromised.

administrative burden on each Hosted System to contact the "key sharing service" as intermediate keys rotate but this is not uncommon.

It is important to note that while the foregoing descriptions treat keys as "all or nothing" entities, all these scheme have corresponding "split key" implementations to achieve higher security. In addition, any security domain may elect to have an authorized Cloudproxy Hosted System archive data. Such an archive application, upon which security domain policy confers access to data, can, in the background, archive data to (centralized or distributed) repositories. There are many other possible mechanisms to do key management but these should get you started.

There is a further discussion of key management in a Cloudproxy environment in [5] as it affects deployment of Cloudproxy applications.

Suggested Exercises

That's all there is to using Cloudproxy. Here are some suggested exercises to complete the training:

1. Write a more complicated set of domain applications; for example, see "`$CLOUDPROXYDIR/go/apps/fileproxy`."
2. Boot a Linux Host System on TPM supported hardware using the TPM to root the Linux Tao (see … for instructions).
3. Boot a KVM Host System on tpm supported hardware and then run a stacked VM host in a Linux partition (see … for instructions). SimpleExample should run fine in the VM(s) with slight changes to the initialization scripts.
4. Explore the Data log engine (examples?)
5. What happens if you make a modification to simpleclient.go and immediately run it on `linux_host` without reinitializing the domain?
6. Write and compile some Datalog rules to do some fancier authorization and try it.
7. Understand how to start Hosted Systems by studying "`$CLOUDPROXYDIR/go/apps/tao_launch`."
8. Correct any errors in this paper or the examples and send the corrections or suggestions to us.
9. Write an awesome Cloudproxy based application and tell us and you friends' about it.
10. Repeat step 9 and have fun!

References

[1] Manferdelli, Roeder, Schneider, The CloudProxy Tao for Trusted Computing, http://www.eecs.berkeley.edu/Pubs/TechRpts/2013/EECS-2013-135.pdf.
[2] CloudProxy Source code, http://github.com/jlmucb/cloudproxy. Kevin Walsh and Tom Roeder were principal authors of the Go version.

[3] TCG, TPM specs,
http://www.trustedcomputinggroup.org/resources/tpm_library_specification
[4] Beekman, Manferdelli, Wagner, Attestation Transparency: Building secure Internet services for legacy clients**.** AsiaCCS, 2016.
[5] Manferdelli, Roeder, Telang, Nuts and Bolts of Deploying Real Cloudproxy Applications. Doc directory in [2].

Cloudproxy Guards

The Guard interface:

- `Subprincipal() auth.SubPrin`: returns a unique subprincipal for this policy.
- `Save(key *Signer) error`: writes all persistent policy data to disk, signed by key
- `Authorize(name auth.Prin, op string, args []string) error`
- `Retract(name auth.Prin, op string, args []string) error`
- `IsAuthorized(name auth.Prin, op string, args []string) bool`
- `AddRule(rule string) error`
- `RetractRule(rule string) error`
- `Clear() error`: removes all rules.
- `Query(query string) (bool, error)`
- `RuleCount() int`
- `GetRule(i int) string`.
- `String() string`: returns a string suitable for showing auth info.

CloudProxy's Authorization Language

Package *auth* implements Tao authorization and authentication, by defining and implementing a logic for describing principals, their trust relationships, and their beliefs.

The grammar for a formula in the logic is roughly:

```
Form ::= Term [from Time] [until Time] says Form
       | Term speaksfor Term
       | forall TermVar : Form
       | exists TermVar : Form
       | Form implies Form
       | Form or Form or ...
       | Form and Form and ...
       | not Form
       | Pred | false | true
```

Quantification variables range over Terms.

```
TermVar : Identifier
```

Times are integers interpreted as 64-bit Unix timestamps.

```
Time ::= int64
```

Predicates are like boolean-valued pure functions, with a name and zero or more terms as arguments.

```
Pred ::= Identifier(Term, Term, ...)
       | Identifier()
```

Terms are concrete values, like strings, integers, or names of principals.

```
Term ::= Str | Bytes | Int | Prin | PrinTail | TermVar
```

Int can be any Go int. Str is a double-quoted Go string. Bytes is written as pairs of hex digits, optionally separated by whitespace, between square brackets. Bytes can also be written as base64w without whitespace between curly braces.

Principal names specify a key or a tpm, and zero or more extensions to specify a sub-principal of that key.

```
PrinType ::= key | tpm
Prin ::= PrinType(Term)
       | PrinType(Term).PrinExt.PrinExt...
PrinExt ::= Identifier(Term, Term, ...)
          | Identifier()
```

Principal tails represent a sequence of extensions that are not rooted in a principal. They are used to make statements about authorized extensions independent of the root principal. For example, they are used to specify that a given program is authorized to execute on any platform. A PrinTail must be followed by at least one extension.

```
PrinTail ::= ext.PrinExt.PrinExt...
```

Identifiers for predicate and principal extension names and quantification variables are limited to simple ascii printable identifiers, with initial upper-case, and no punctuation except '_':

```
PredName ::= [A-Z][a-zA-Z0-9_]*
ExtName ::= [A-Z][a-zA-Z0-9_]*
```

The keywords used in the above grammar are:

```
from, until, says, speaskfor, forall, exists, implies, or, and, not, false,
true, key
```

The punctuation used are those for strings and byte slices, plus:

```
'(', ')', ',', '.', ':'
```

It is possible to represent nonsensical formulas, so some sanity checking maybe called for. For example, in general:

1. The left operand of Says should be Prin or TermVar, as should both operands of Speaksfor.
2. All TermVar variables should be bound.
3. Conjunctions should have at least one conjunct.
4. Disjunctions should have at least one disjunct.
5. Identifiers should be legal using the above rules.
6. The parameter for key() should be TermVar or Bytes.

Specific applications may impose additional restrictions on the structure of formulas they accept.

All of the above elements have three distinct representations. The first representation is ast-like, with each element represented by an appropriate Go type, e.g. an int, a string, or a struct containing pointers (or interfaces) for child elements. This representation is meant to be easy to programmatically construct, split apart using type switches, rearrange, traverse, etc.

The second representation is textual, which is convenient for humans but isn't canonical and can involve tricky parsing. When parsing elements from text:

Whitespace is ignored between elements (except around the subprincipal dot operator, and before the open paren of a Pred, Prin, or, PrinExt) operator, and before the open parenthesis of a Pred, Prin, or, PrinExt).

For binary operators taking two Forms, the above list shows the productions in order of increasing precedence. In all other cases, operations are parsed left to right. Parenthesis can be used for specifying precedence explicitly.

When pretty-printing elements to text, a single space is used before and after keywords, commas, and colons. Elements can also be pretty-printed with elision, in which case keys and long strings are truncated.

The third representation is an encoded sequence of bytes. This is meant to be compact,

relatively easy to parse, and suitable for passing over sockets, network connections, etc. The encoding format is custom-designed, but is roughly similar to the format used by protobuf.

The encoding we use instead is meant to be conceptually simple, reasonably space efficient, and simple to decode. And unlike most of the other schemes above, strictness rather than flexibility is preferred. For example, when decoding a Form used for authorization, unrecognized fields should not be silently skipped, and unexpected types should not be silently coerced.

Each element is encoded as a type tag followed by encodings for one or more values. The tag is encoded as a plain (i.e. not zig-zag encoded) varint, and it determines the meaning, number, and types of the values. Values are encoded according to their type:

An integer or bool is encoded as plain varint.

A string is encoded as a length (plain varint) followed by raw bytes.

A pointer is encoded the same as a boolean optionally followed by a value.

Variable-length slices (e.g. for conjuncts, disjuncts, predicate arguments) are encoded as a count (plain varint) followed by the encoding for each element.

An embedded struct or interface is encoded as a tag and encoded value.

Differences from protobuf: Our tags carry implicit type information. In protobuf, the low 3 bits of each tag carries an explicit type marker. That allows protobuf to skip over unrecognized fields (not a design goal for us). It also means protobuf can only handle 15 unique tags before overflowing to 2 byte encodings.

Our tags describe both the meaning and the type of all enclosed values, and we use tags only when the meaning or type can vary (i.e. for interface types). Protobuf uses tags for every enclosed value, and those tags also carry type information. Protobuf is more efficient when there are many optional fields. For us, nearly all fields are required.

Enclosed values in our encoding must appear in order. Protobuf values can appear in any order. Protobuf encodings can concatenated, truncated, etc., all non-features for us.

Note: In most cases, a tag appears only when the type would be ambiguous, i.e. when encoding Term or Form.

SimpleExample in C++

Simple Client in C++

Simple Server in C++